# Non-thermal magnetospheric process in AGN

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# General remarks

Formation of jets is reasonably well understood. But!

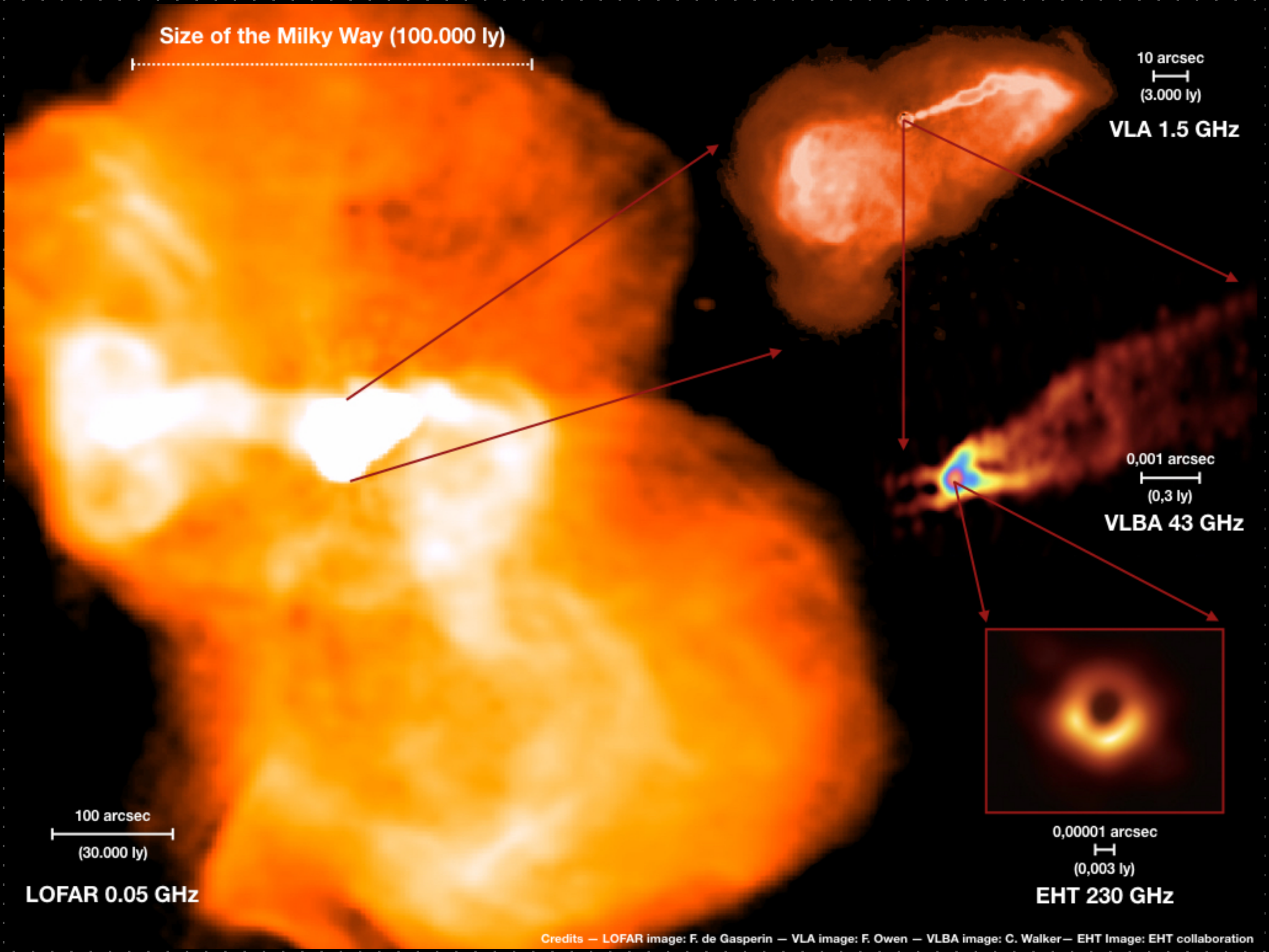
- what is the dissipation mechanism?
- origin of plasma source in the magnetosphere?
  (external pp, spark gap, etc)

# This talk

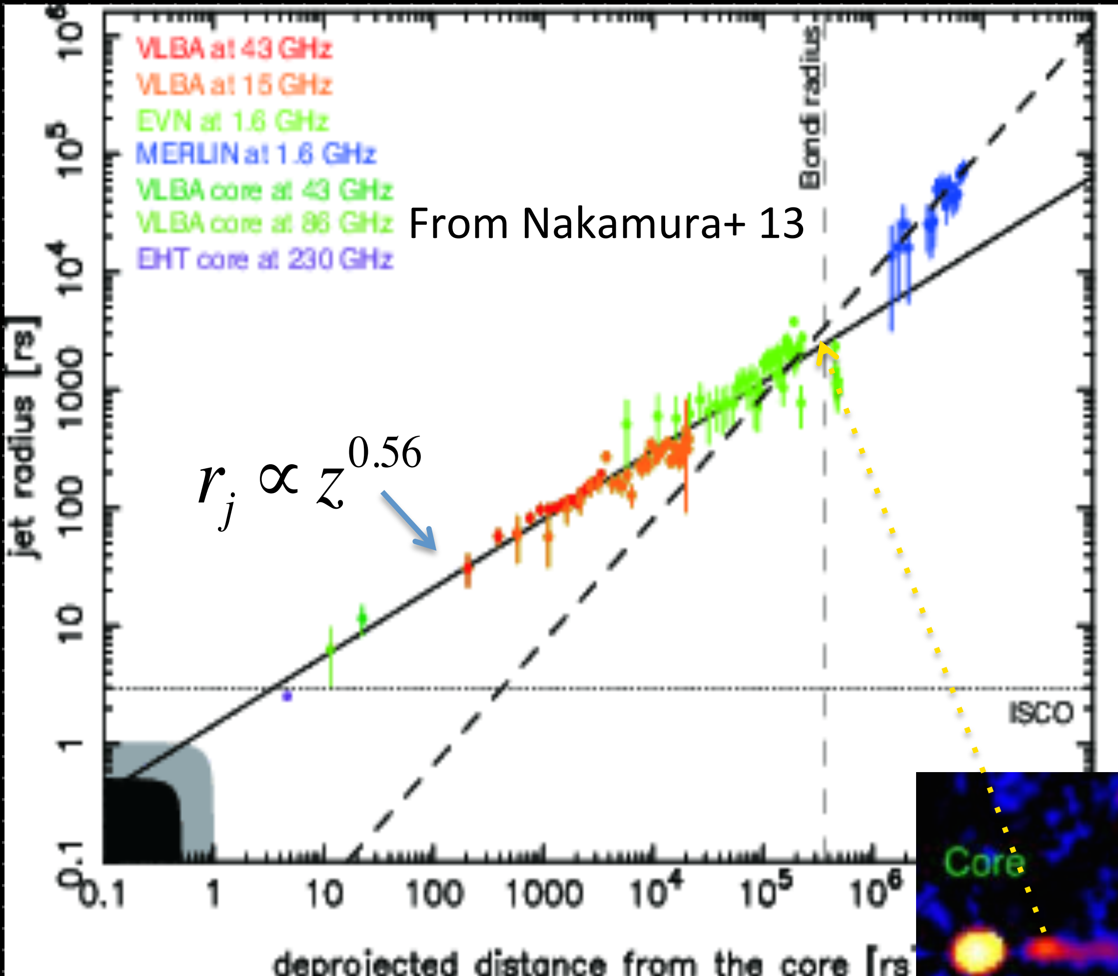
- Plasma injection in BH magnetosphere and consequences for high-energy emission
- Preliminary results of 3D FF simulations of loop accretion

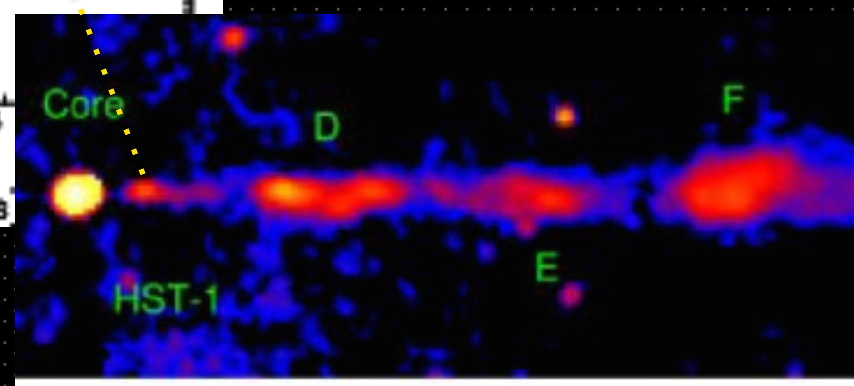
# M87

BZ mechanism works



# M87 - collimation profile

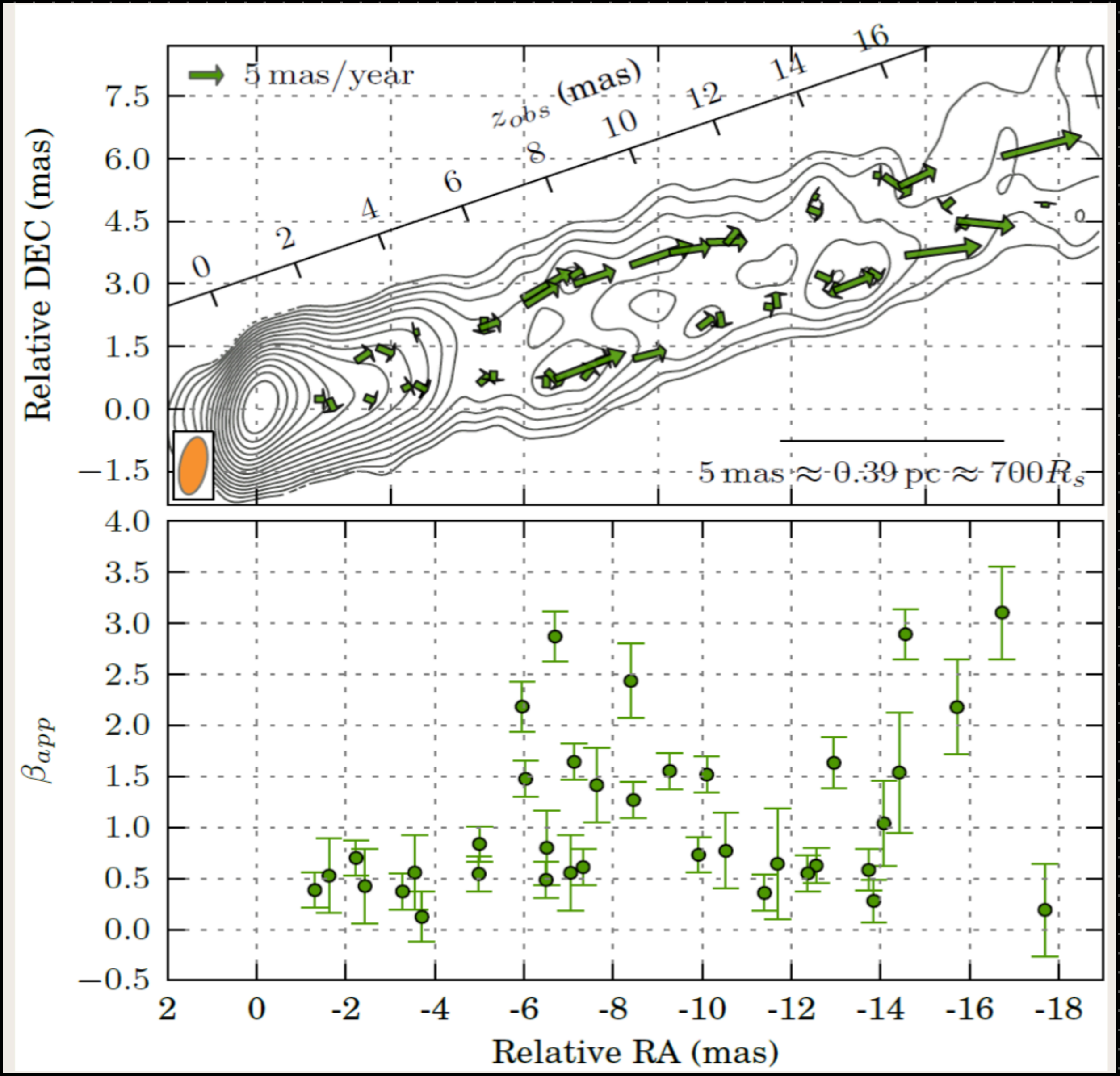



Collimation break associated with the HST-1 knot

# Stratified flow in M87

Mertens + 16



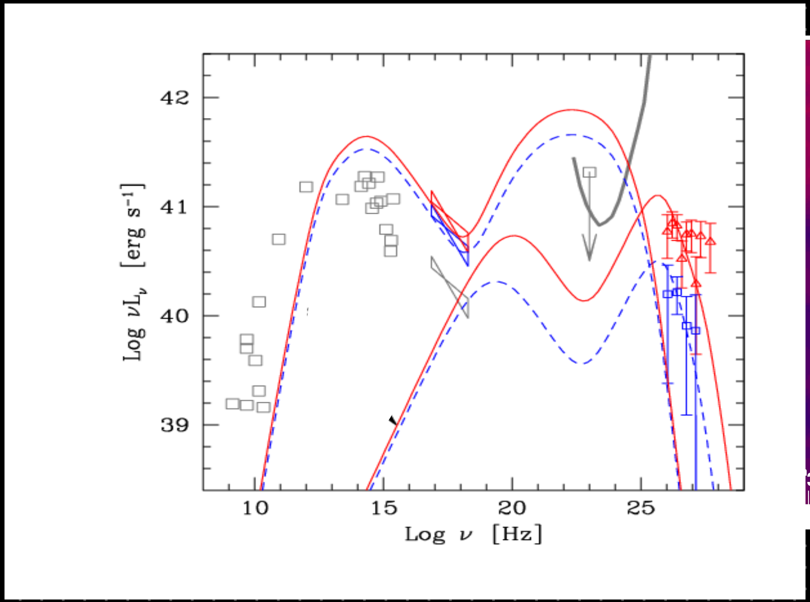
# M87

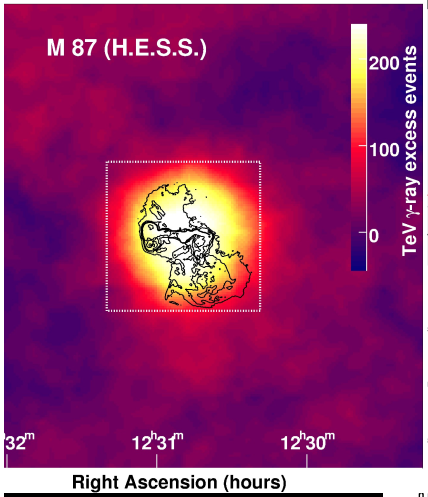
Strong flares observed in 2005, 2008, 2010

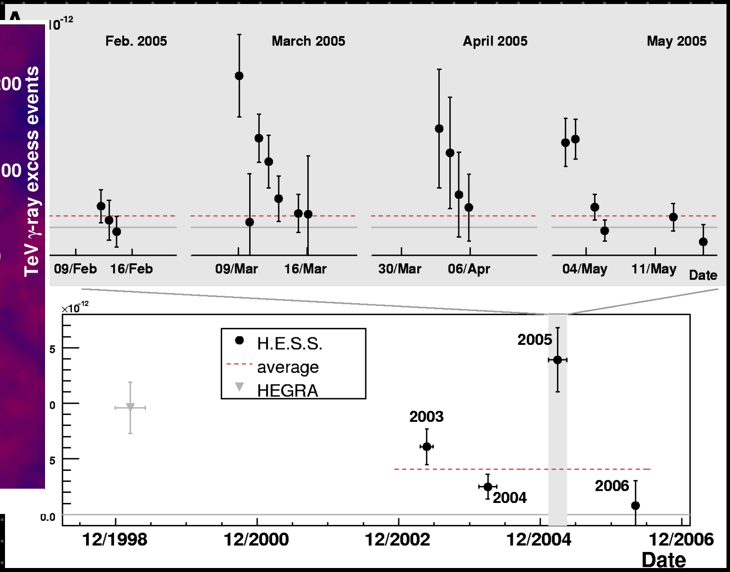
$L_j \approx 10^{43}$ erg $s^{-1}$,   $L_\gamma \approx 10^{41}$ erg $s^{-1}$

Variability time ≈ 1 day ~ $r_s$

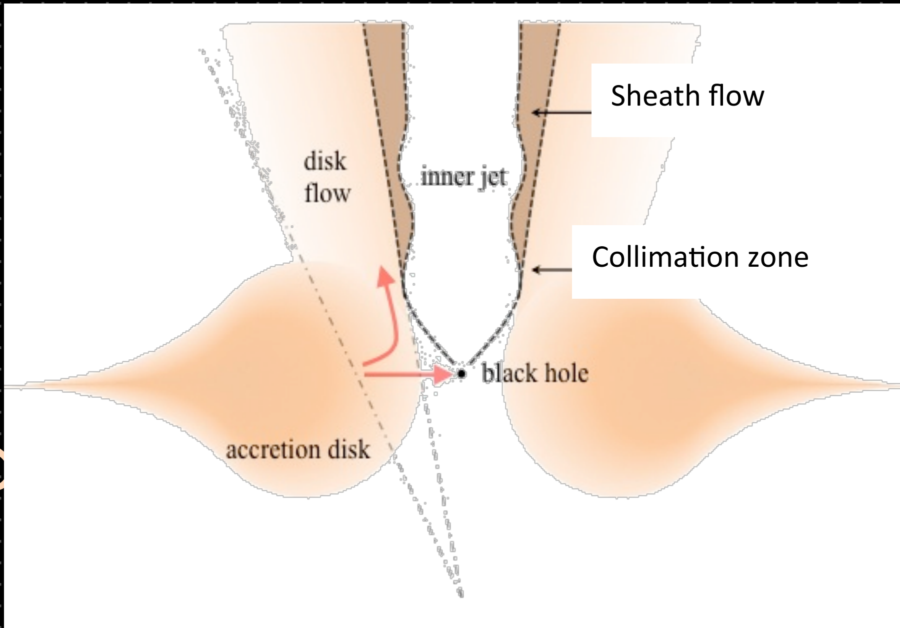
TeV emission from inner region or a remote, small region?



# Multi-flow




Two flow MHD model
(Garcia + '09; Nakamura + Asada '13)

Jet-sheath structure in GRMHD simulations (Moscibrodzka + '13)

disk winds (McKinney '06; Globus + AL '16)

- Slow components from sheath flow ?
- Relativistic components + HE emission (particularly variable TeV emission) from inner jet ?

# Emission from sheath flow

Proton temp. in accretion flow is virial: $T_p \sim 0.1\, m_p c^2$

and $T_e/T_p < 1 \;\Rightarrow\; \gamma_{e,th} < 10^2$ .

- Radio emission at small radii arises from sheath.
- VHE emission from sheath requires effective electron acceleration there !

Variable TeV emission from inner jet? Sheath?
Requires rapid dissipation of B field !!

# I. Plasma production and activation of BH outflows

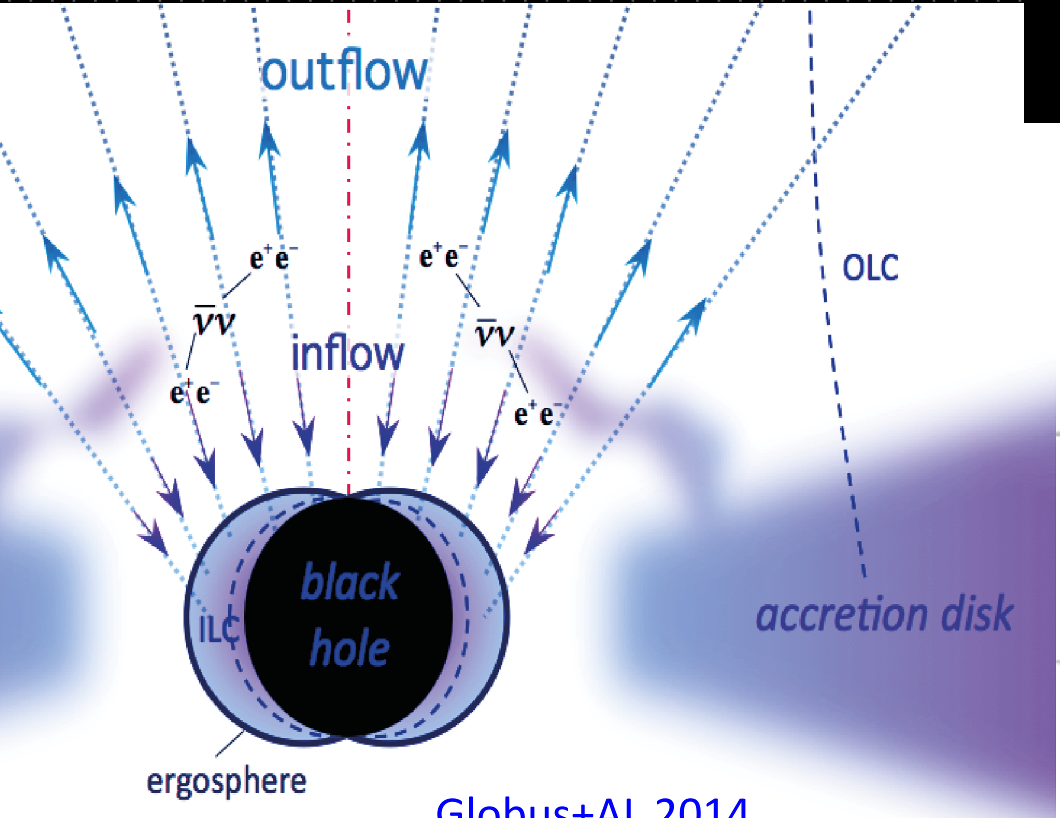
# Plasma injection in the magnetosphere

- plasma source between inner and outer Alfven surfaces
- escape time ≈ few $r_g/c$

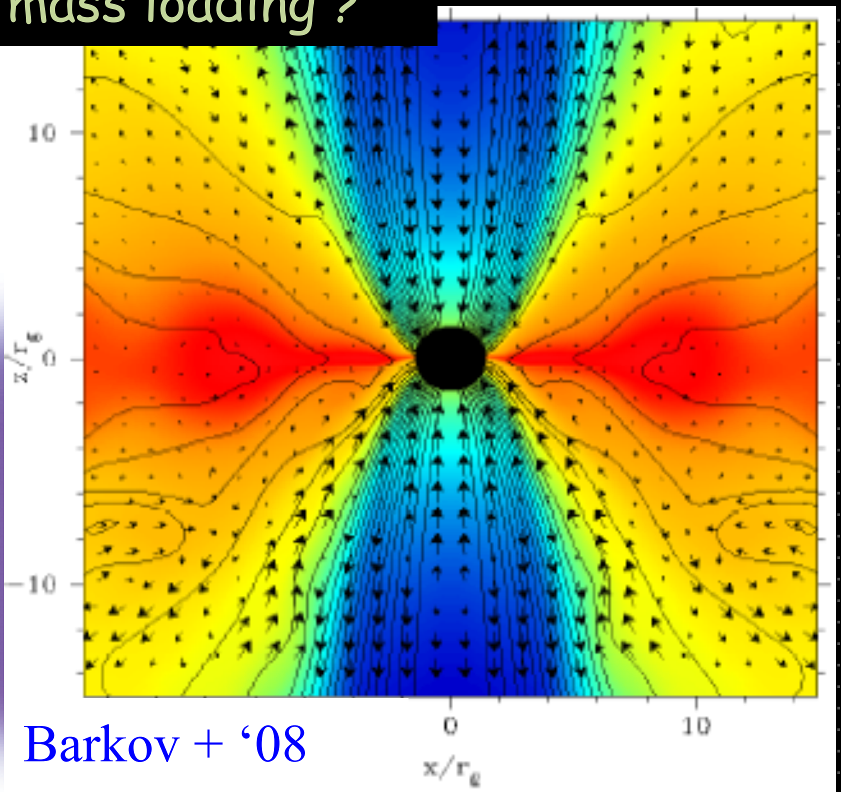
$\gamma\gamma \to e^{\pm}$ in AGNs

$\nu\nu \to e^{\pm}$ in GRBs

mass loading ?

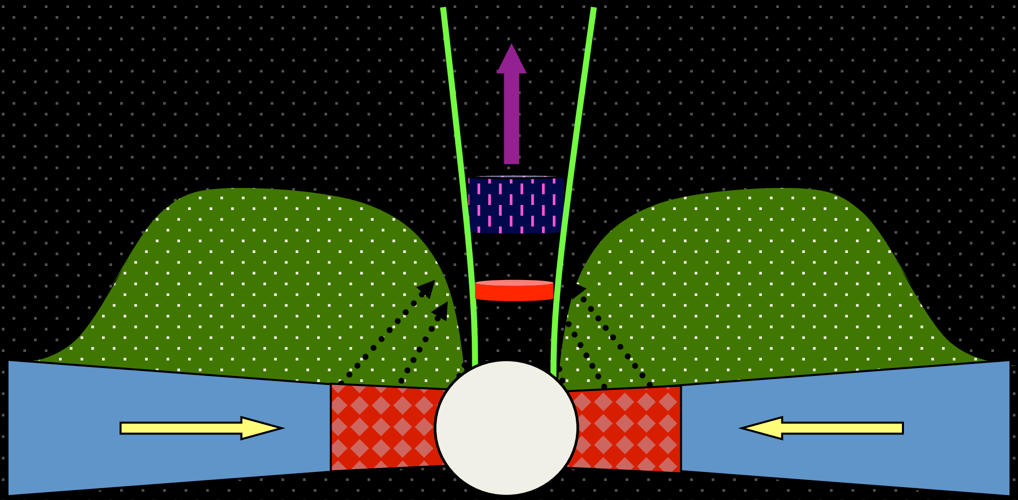



Globus+AL 2014




Barkov + '08

# How to produce the required charge density?



- Protons from RIAF ?
- Protons from n decay ?
- $e^{\pm}$ from $\gamma\gamma$ annihilation ?
- Other source ?

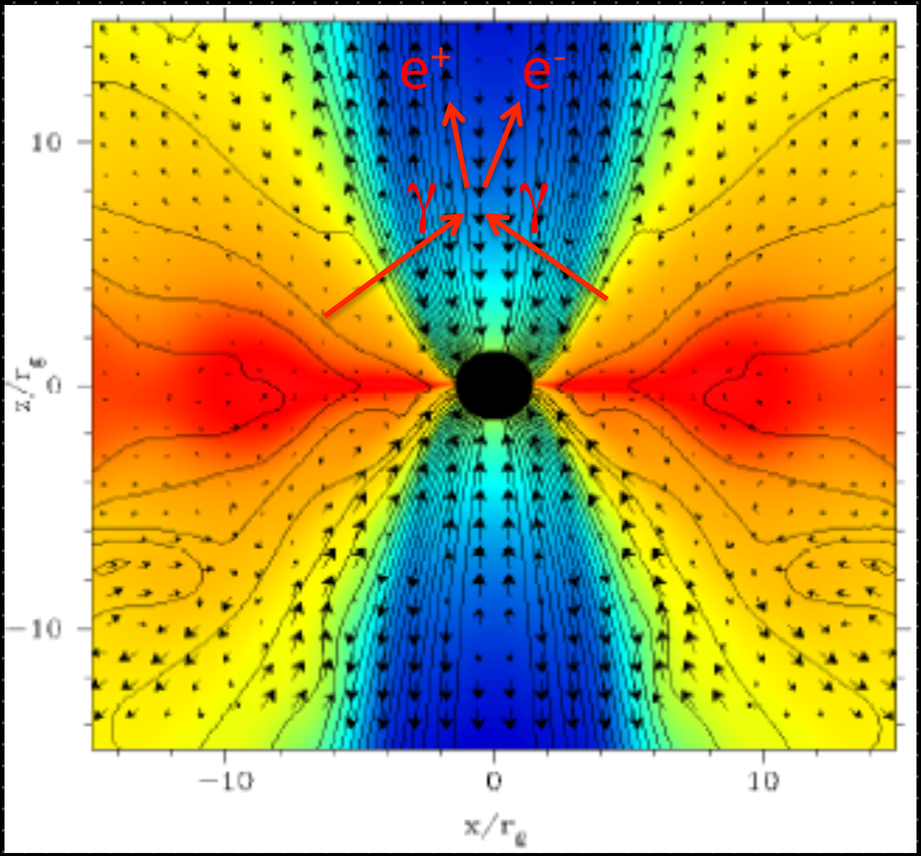
➢ Protons have to cross magnetic field lines. Diffusion length over accretion time extremely small.

➢ instabilities or field reversals. But intermittent spark gaps may still form.

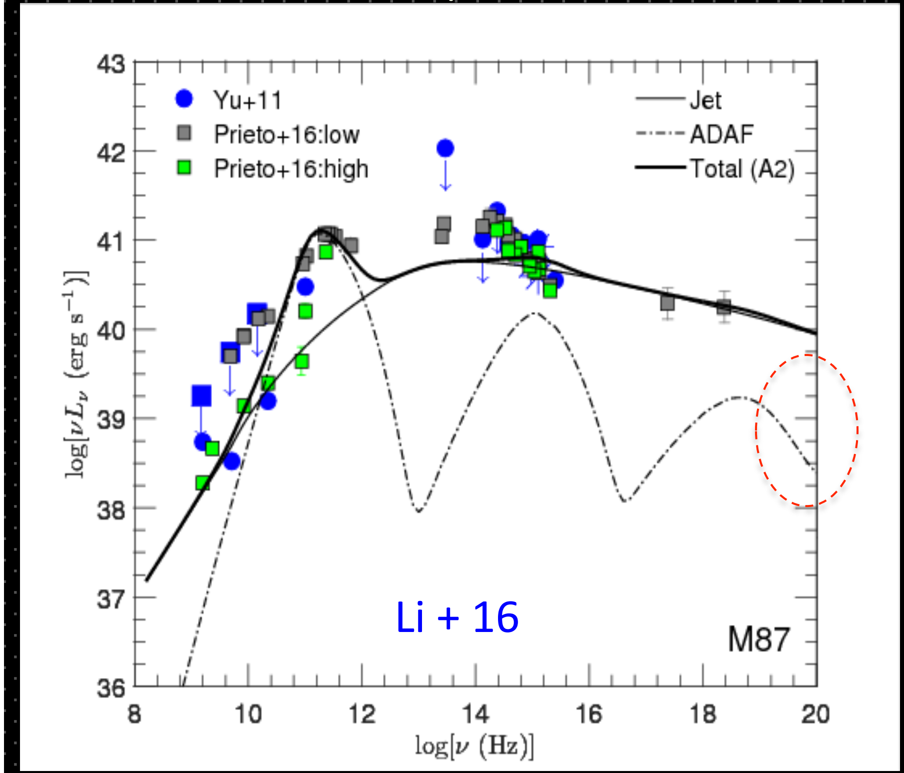
# Direct pair injection by $\gamma\gamma \rightarrow e^{\pm}$

Requires emission of MeV photons:

- Low accretion rates: from hot accretion flow
- High accretion rate: from corona ?

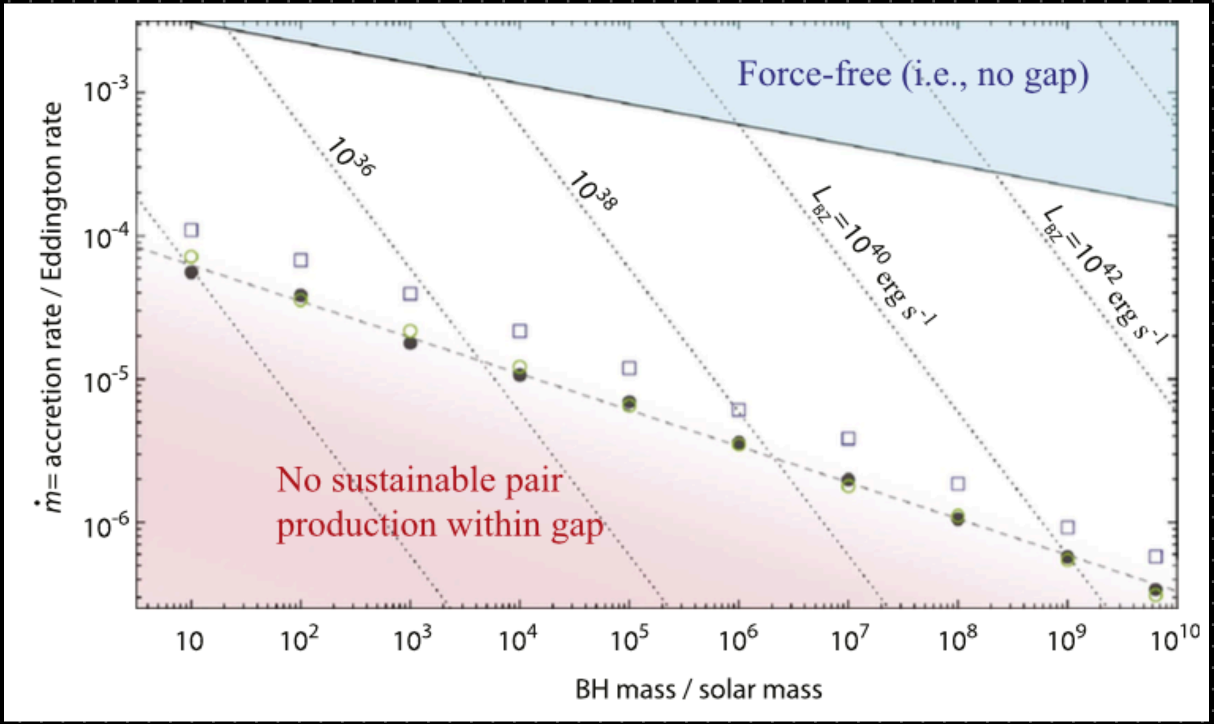



Example: M87



# Direct pair injection

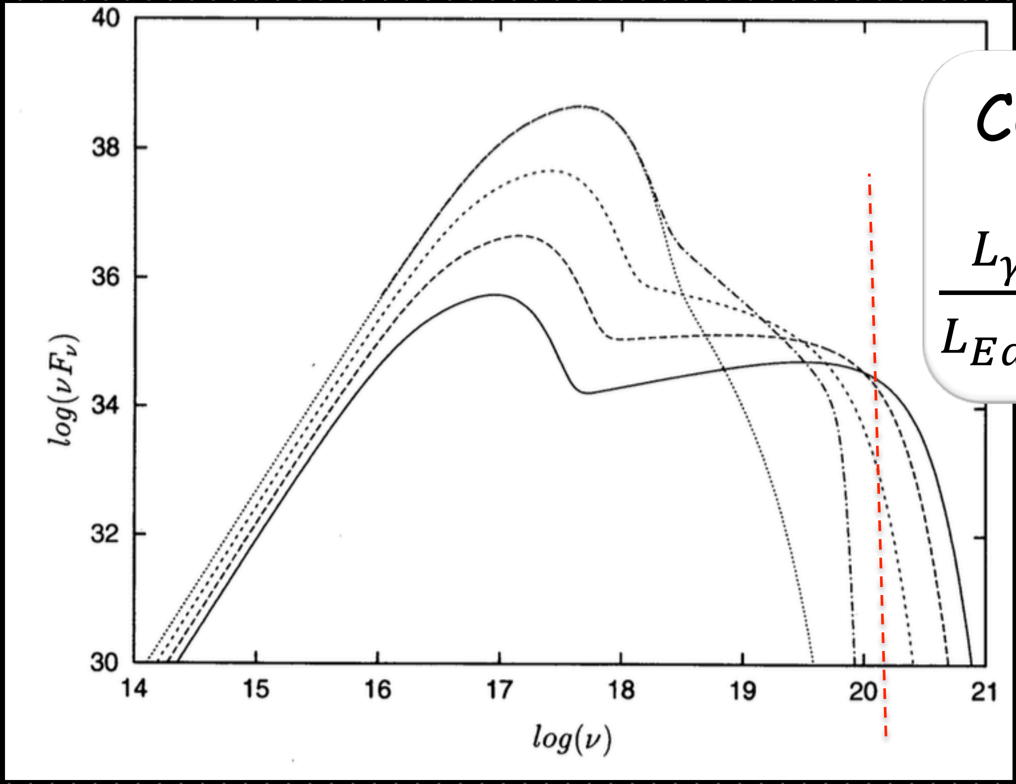
- Low accretion rates (RIAF): AC may be hot enough to produce gamma-rays above threshold (Levinson +Rieger 11, Hirotani + 16)




Conditions for gap formation (From Hirotani+ 16)

# Criteria for gap formation: non-RIAF

- Intermediate accretion rates: Disk is cold, but corona may scatter photons to MeV energies.




Model SED of a 5 $M_o$ BH at different states
(from Chakrabarti + 95)

Condition for gap formation

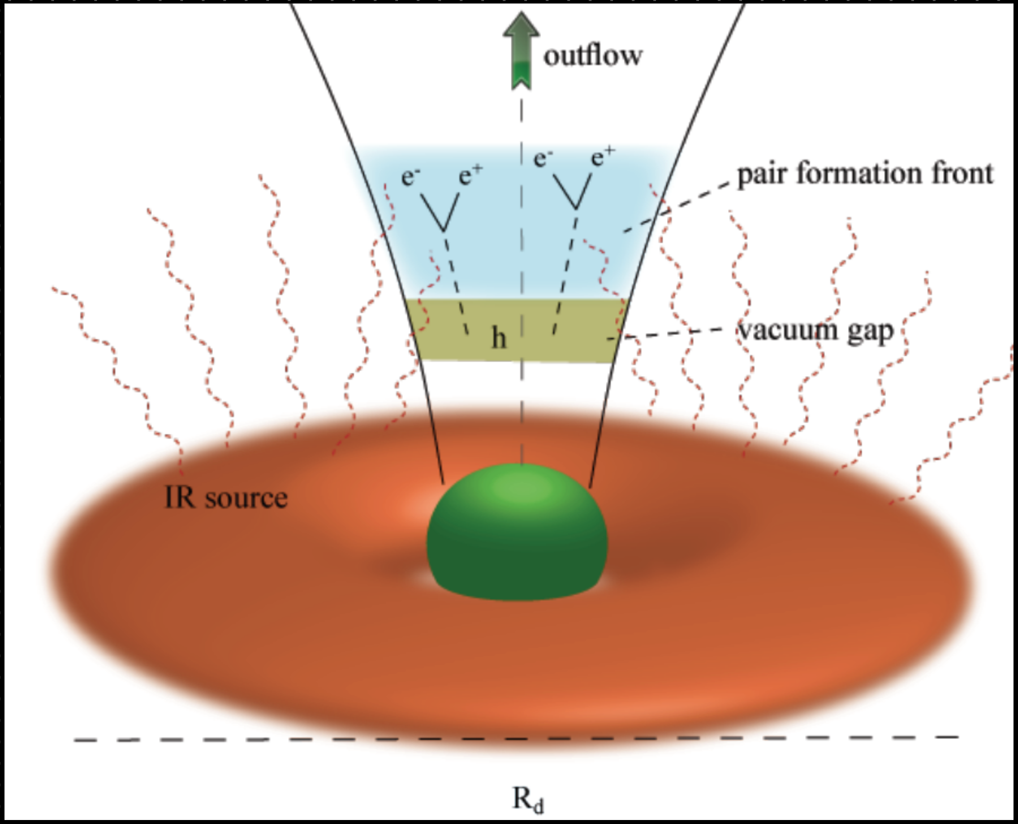
$$\frac{L_\gamma}{L_{Edd}} < 10^{-3}\left(\frac{B}{10^8\ G}\right)^{1/2}\left(\frac{R_\gamma}{30\ r_g}\right)^2$$

Stellar BH: $B \approx 10^8\,G$

AGNs: $B \approx 10^4\,G$

# Activation of a spark gaps

AL 00; Neronov + '07, AL + Rieger '11, Broderick + 15; Hirotani+ 16, 17




- activated when $n < n_{GJ}$ . Expected in M87 when accretion rate < $10^{-4}$ Edd.
- must be intermittent (Segev+AL 17).
- particle acceleration to VHE by potential drop.

# GRPIC Simulations

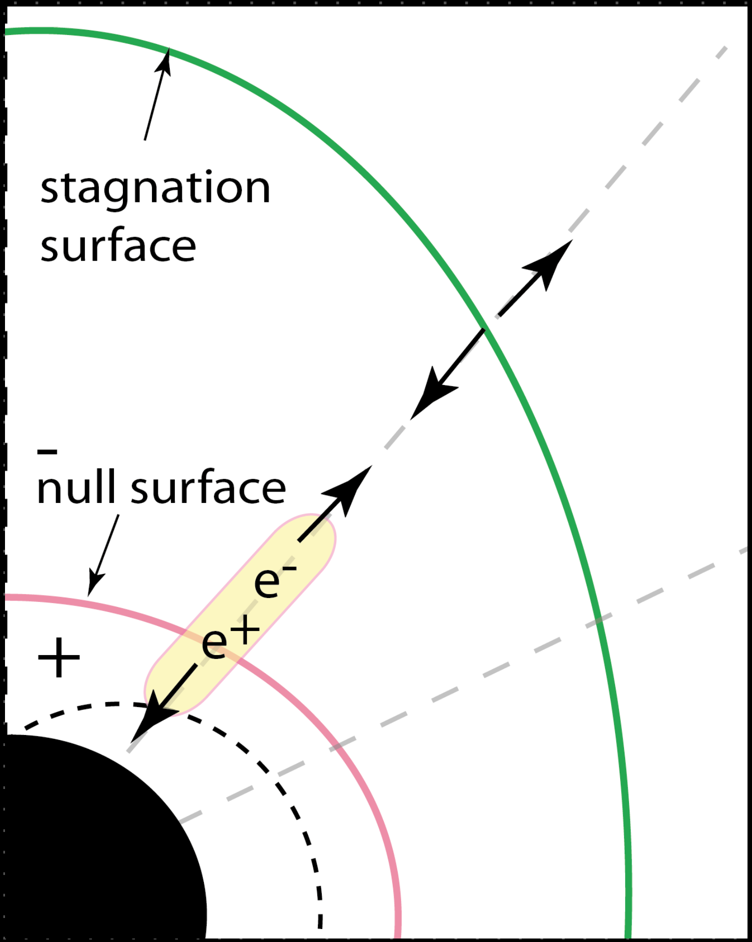
With Benoit Cerutti and his Zeltron code

- Fully GR (in Kerr geometry)
- Inverse Compton and pair production are treated using Monte-Carlo approach.
- Curvature emission + feedback included
- Currently 1D local gaps
- Goal: 2D global simulations

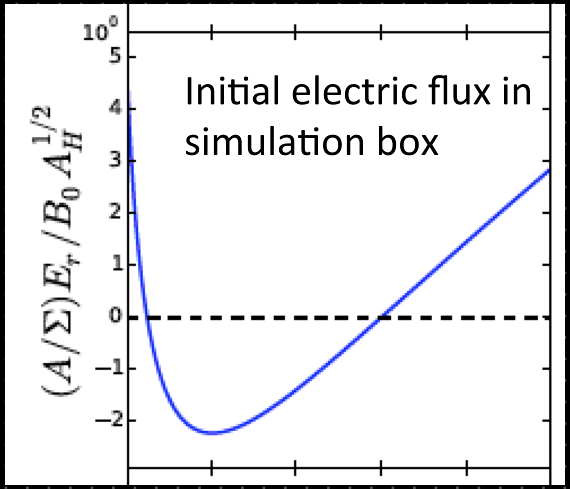
# 1D model

AL + Cerutti 18

Global structure




- Solves GRPIC equations along a particular field line
- Magnetospheric current is a given parameter



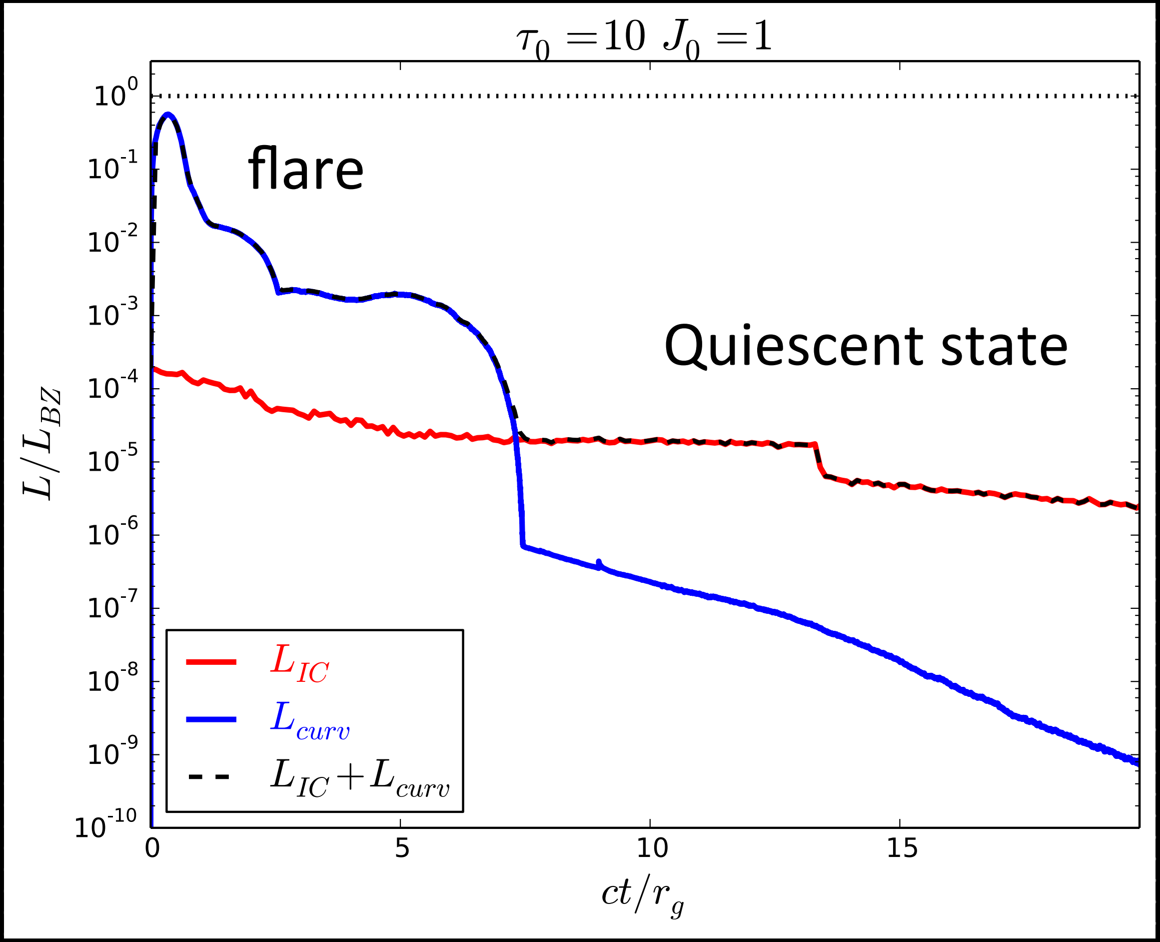
# Example

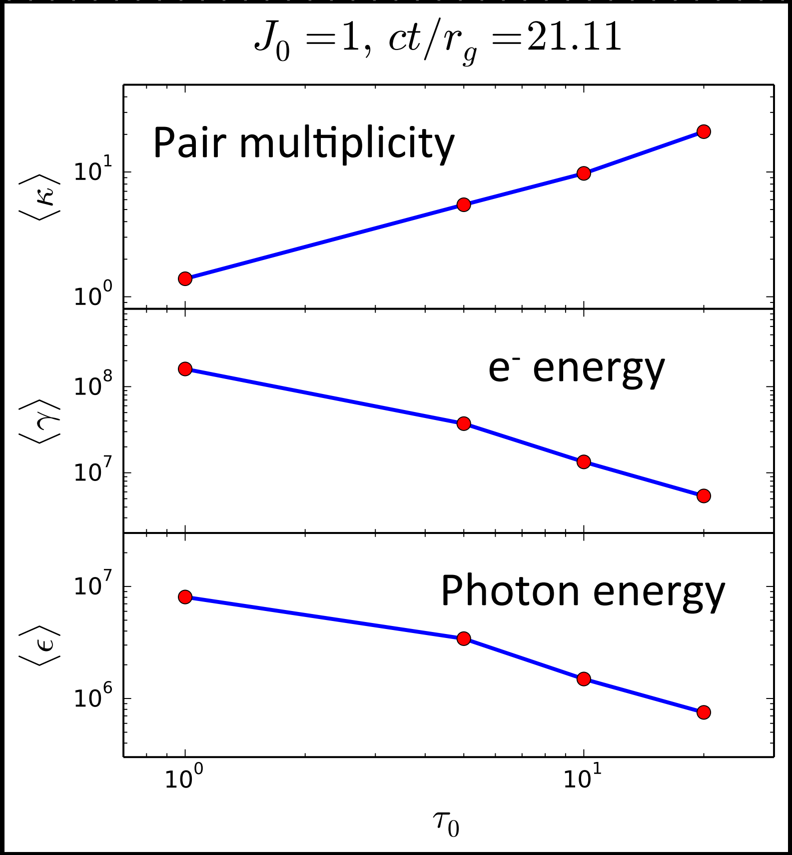
$\tau_0 = \sigma_T n_{ph} r_g \sim$ Pair-production opacity across gap

$$\tau_0 = 10$$

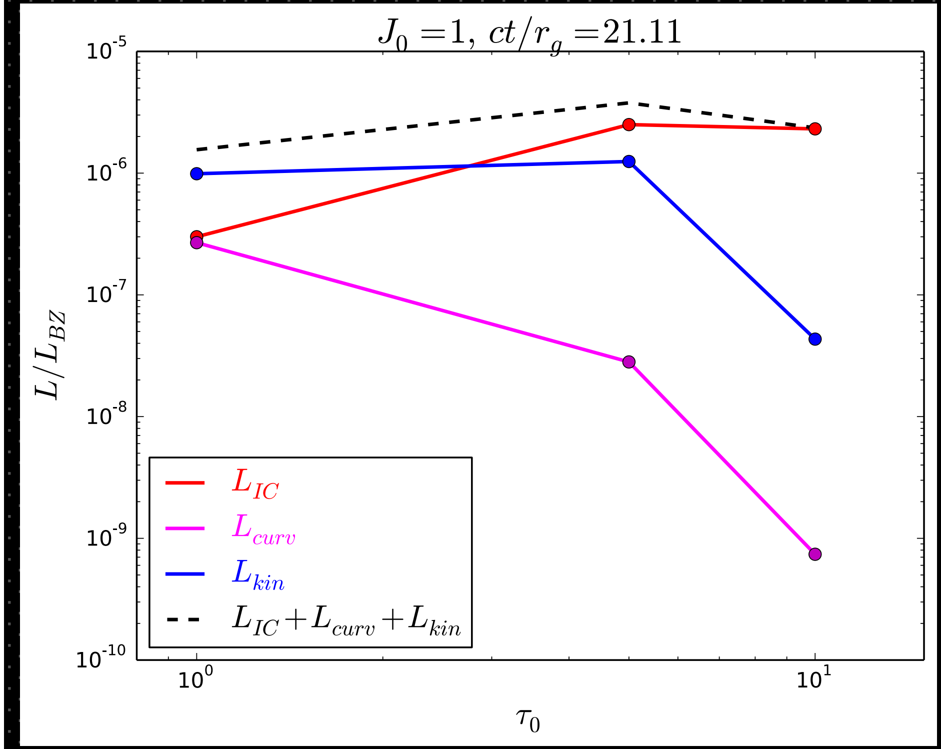
Radiation reaction limit

# γ Light curve






# Luminosity during quiescent state



$$\tau_0 = 0.01$$

# M87- radio emission ?

$r_s \approx 1.8\times10^{15}$ cm $\approx 1$ day , $L_{EHT} \approx 3\times10^{40}$ erg/s

Density of emitting electrons:

$$n_e = \frac{L_{EHT}}{P_{syc} V} \sim 10^5 (R/r_s)^{-3} B^{-1} \text{ cm}^{-3}$$

GJ density: $n_{GJ} \approx 10^{-7}(2\Omega/\omega_H)B$ cm$^{-3}$

So, not from a gap! Most likely from sheath

If from jet (baryonic matter):

$$L_j > 10^{43}\ (n_p/n_e)\Gamma^2 B^{-1}(R/r_s)^{-1} \text{ erg/s}$$

# II. Dissipation of magnetized jets

## Large scale (ordered) B fields:

efficient jet production (MAD, MCAF, etc.)

but stable! dissipation requires rapid growth of instabilities

## Small scale B field:

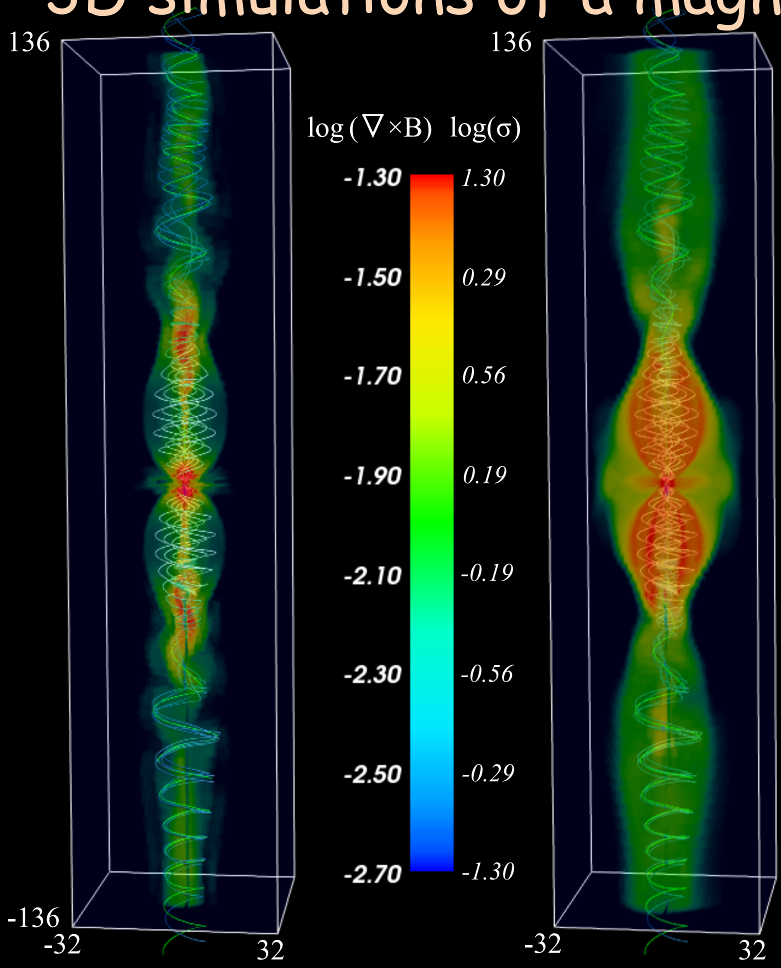
quasi-striped configuration (good for dissipation and loading)

Smaller efficiency

# Dissipation of ordered field

## Small angle reconnection via CD kink inst.

3D simulations of a magnetic jet propagating in a star

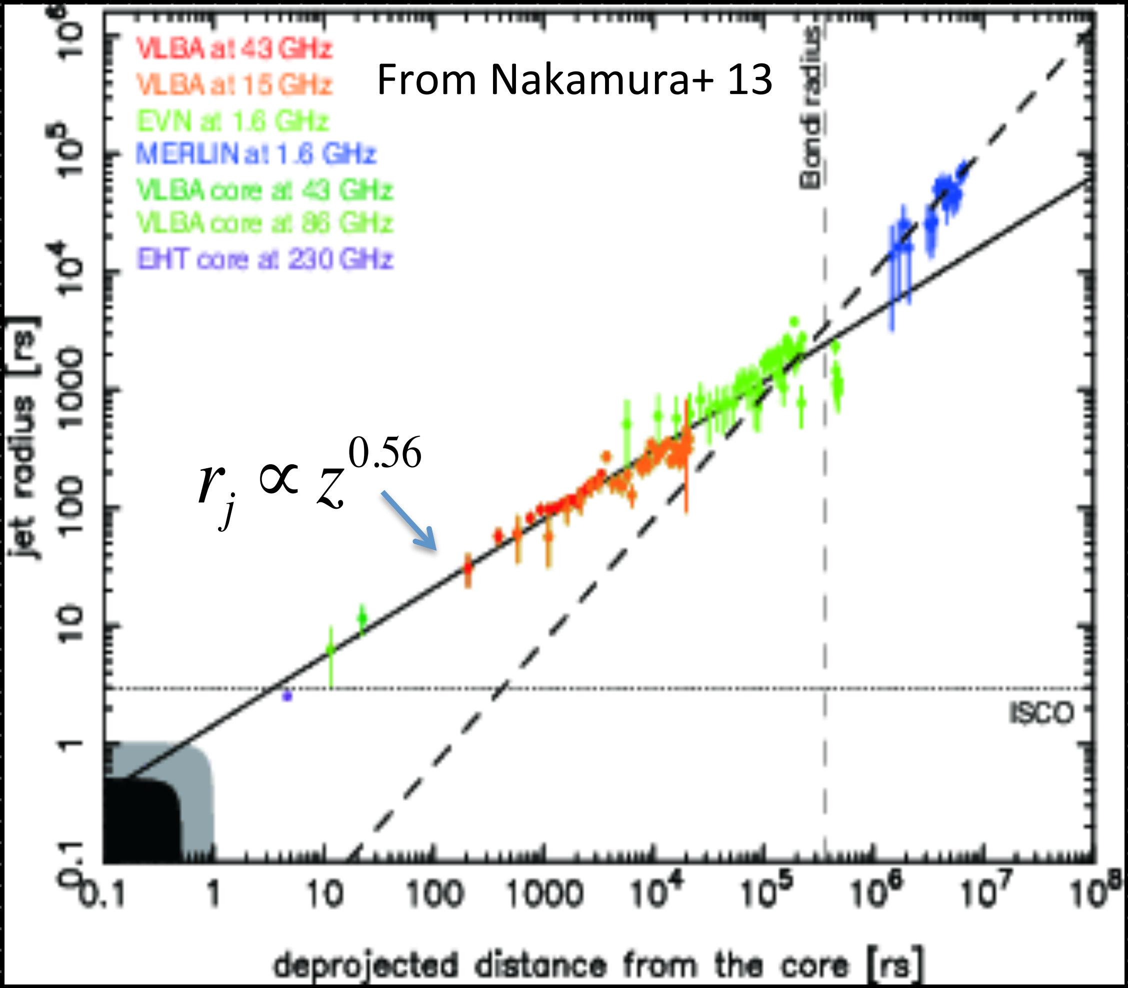



Bromberg + Tchekhovskoy ‘16

kink instability requires strong collimation. Develops fastest in a collimation nozzle.

But even then, saturates at equipartition.

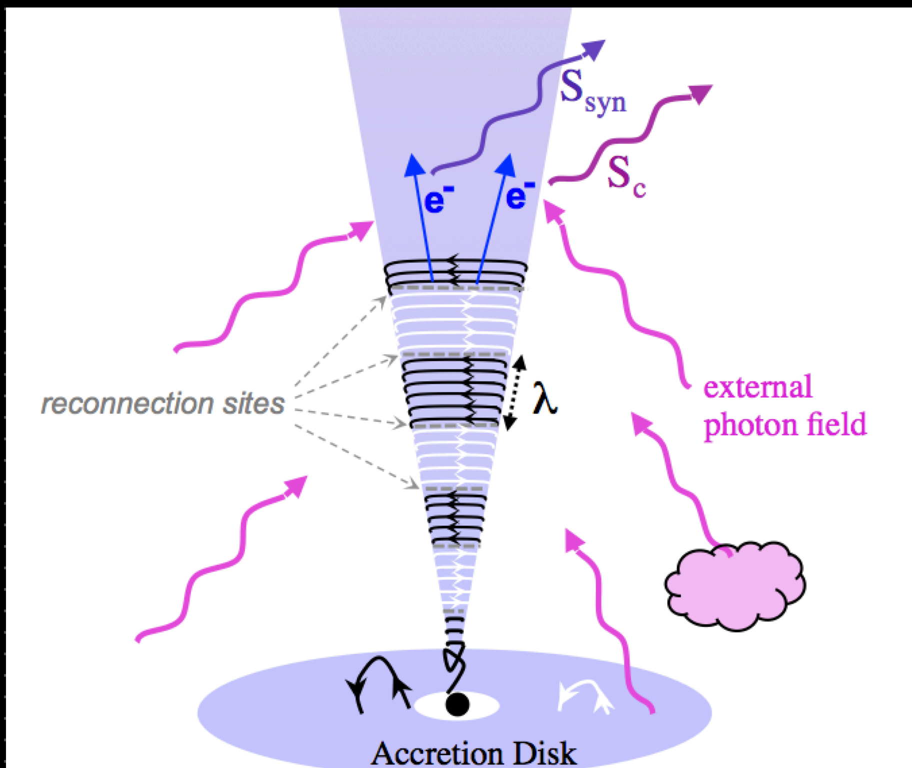
# M87 – parabolic jet




Is this jet stable or not ?

# quasi-striped jet

## Reconnection of non-symmetric component




Romanova + Lovelace 92
AL + Van Putten 97
Drenkhahn + Spruit '02
AL+Globus '16

Dissipation on scales:

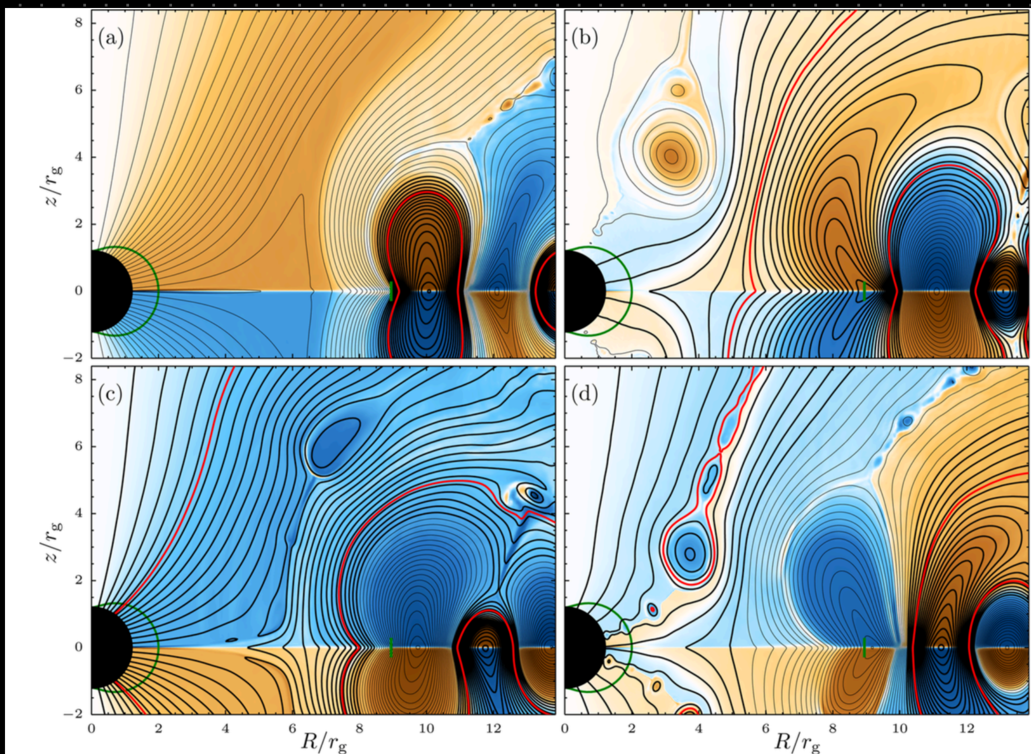
$$r_{diss} \sim \lambda \Gamma_0^2 \beta_{rec}^{-1} \gg r_g$$

Difficult to account for extreme flares (but see next)

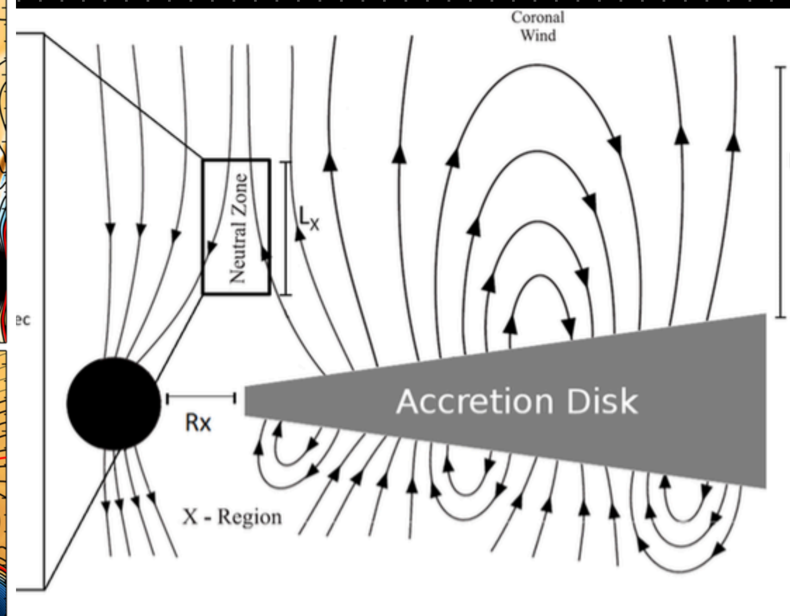
# Accretion of flux loops

Spruit, uzdenski, goodman

Reconnection can lead to electron acceleration in the jet + sheath. Potential site of VHE emission.




2D Simulations by Parfrey + '15




Van Putten + AL '03

Kadowaki, de Gouveia Dal Pino + '15

# 3D GRFF simulations of loop accretion

Jens Mahlmann (with M. Aloy and AL)

Preliminary results

# Conclusions

- spark gaps may form if survival time of coherent magnetic domains exceeds a few dynamical times. May be the production sites of variable VHE emission.
- gaps are inherently intermittent.
- Pair discharges by rapid plasma oscillations, emitting TeV photons with $L_{TeV}/L_{BZ} \sim 10^{-5}$.
- strong TeV flares can be produced if gap is restored
- Loop B accretion may produce favorable dissipation sites near the BH.